THE DIFFUSE INTERSTELLAR MEDIUM WITH THE HERSCHEL SPACE OBSERVATORY

M. Gerin^{1,2}, M.A. Miville-Deschênes^{1,2,3}, and P. Hennebelle^{1,2}

^{1}Laboratoire de Radioastronomie Millimétrique, UMR 8540 du CNRS,
Département de Physique de l'E.N.S., 24 Rue Lhomond, 75231 Paris cedex 05, France
^{2}DEMIRM, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France
^{3}Département de Physique, Observatoire astronomique du Mont Mégantic, Université Laval, Sainte-Foy, Québec, G1K 7P4, Canada

Abstract

The Herschel Space Observatory will make important contributions to most fields of astrophysics. Sensitive observations at high spatial and/or spectral resolution will permit to study extensively the physical and chemical properties of the diffuse interstellar medium, both in our Galaxy and in external galaxies. We present specific subjects for which observations with Herschel are expected to make decisive contributions. The small scale structure of the diffuse ISM, in connection with the global thermal balance of the ISM in the Galactic disk, the evolution of dust properties from ionised gas to neutral atomic clouds to molecular regions, and the chemistry of diffuse clouds are among the most promising themes.

Key words: ISM : clouds – ISM: structure – ISM : chemistry – Dust: properties – Photo-dissoci ation regions

---

1. Introduction

The identification and detailed description of the physical processes determining the properties of astrophysical objects is a mandatory step in establishing a good physical model of astrophysical sources. Studies of the diffuse interstellar medium, i.e. regions of the ISM permeated by UV photons are among the best ways to increase our knowledge on the photo-processes ruling the physical, thermal and chemical properties of UV illuminated gas. Photo-processes studied in this context are also important for many other astrophysical media, such as the close environment of young stars or Active Galactic Nuclei.

The concept of "diffuse interstellar medium" thus extends from low column density ionised gas, to neutral atomic clouds, to the illuminated edges of molecular clouds. As such, it covers an important component of the interstellar medium in galaxies, where most of the energy exchanges between stars and gas take place.

Diffuse interstellar emission is also one of the main foregrounds to be taken into account for the Planck mission. Therefore, the goal of obtaining a good understanding of the properties of the diffuse interstellar emission can be considered as a common science objective for the combined Planck/Herschel project.

The main themes relevant for the Herschel Space Observatory (HSO) are :

- The phases of the interstellar medium
- Chemistry of the diffuse interstellar gas
- Evolution of dust properties from ionised to atomic to molecular gas and the life cycle of interstellar matter

2. The phases of the diffuse ISM

2.1. Ionised gas in the Galaxy

In the Milky Way, the interstellar gas can be found in various neutral or ionised states, or phases. A comprehensive model of the interstellar medium is presented by Ferrière (1998). While most of the mass is found in the neutral phases, with atomic or molecular gas, most of the volume is occupied by the warm and hot phases. There are two ionised states, the hot ionised medium (HIM) and the warm ionised medium (WIM). In the Milky Way, ionised gas in found in HII regions near massive stars. When they escape the vicinity of massive stars, ionising photons may create extended diffuse HII regions, but they also contribute to the overall ionising flux in the Galaxy disk. Ionised gas from diffuse HII regions follows the same large scale distribution as Population I tracers, with a small scale height. In addition to this well understood ionised gas component, there are various observational evidences for a more widespread ionised phase, with a large scale height, the so-called Warm Ionised Medium. In the solar neighbourhood, the widespread presence of diffuse ionised gas has been revealed by a variety of observations, among which diffuse Hα emission (Haffner et al. 1999). The WIM contains the majority of the ionised gas mass in the Galaxy, and fills a significant fraction of its volume though the exact figure remains debated (10% – 40% , Wood & Reynolds 1999). Its scale height has been determined accurately to be $\sim$1 kpc, and the electron temperature rises smoothly from $\sim$ 6000K to $\sim$ 10000K with increasing latitude (Haffner et al. 1999).

Despite these accurate diagnostics, we still lack a good understanding of the physical processes ruling the thermal and physical properties of the WIM (Mathis 2000, Slavin et al. 2000). Most of the observations provide local data on the WIM. Because of the large extinction towards the inner Galaxy, there is almost no information on the ionised gas properties, as a function of the position

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

in the Galaxy, and their connection with the star forming activity. Deep Hα images of edge-on galaxies reveal the presence of ionised gas far from the mid-plane similar to the Galactic WIM. A particularly good example has been found in the edge-on spiral NGC 891 (Rand 1998).

Most diagnostics of the physical conditions in the WIM, and of their spatial distribution are obtained from deep spectroscopy in the visible wavelength range. Complementary informations can be obtained from far infrared lines of ionised carbon at 158μm and nitrogen at 122 and 205 μm, which have been observed throughout the Galaxy with COBE-FIRAS (Fixsen et al. 1999). With high spectral resolution, the distance of the emission sources can be determined accurately from their radial velocity. We can use the [NII] lines to study the radial and vertical distribution of ionised gas, and to determine the electronic density. The aim is to relate the properties of the ionised gas with the star formation activity as the presence of ionised gas is directly linked to the presence of massive stars. Also, the contribution of ionised gas (in HII regions Colbert et al. 1999 or the WIM) to the large scale [CII] emission will be accurately traced. With its ability to cover large fields rapidly and its excellent sensitivity, Herschel will bring new information on the role of the ionised gas in the energy transfers between stars and gas.

2.2. The cold and warm neutral phases

Observations of the neutral atomic gas through the spin-flip line of atomic hydrogen at 21 cm, and theoretical calculations have revealed the presence of two neutral gas phases with well separated properties, the warm neutral medium (WNM, T $\sim$ 8000 K, n $\sim$ 0.4 cm^{-3}) and the cold neutral medium (CNM, T $\sim$ 80 K, n $\sim$ 40 cm^{-3}) approximatively in thermal pressure equilibrium (Kulkarni & Heiles 1987, Wolfire et al. 1995). These two phases appear as velocity components in the HI line profiles, with different line shapes : whereas WNM profiles are broad and smooth, CNM lines are narrow and multiple components can be seen along the line of sight. Due to its lower temperature, the CNM is conspicuous in absorption against bright continuum sources while it is extremely difficult to detect absorption from the WNM (Carilli et al. 1998). The usual way to determine the physical properties of the phases through 21cm data is to compare emission and absorption along the same line of sight. It is much more difficult to study the spatial structure of the phases, and their respective filling factor in the Galaxy from sparse measurements along widely separated lines of sight. The current figure is that the mass of neutral atomic gas is shared approximatively equally between the CNM and WNM (Ferrière 1998).

The small scale structure of the neutral phases and their relative spatial distribution is a critical information to understand the link between the CNM and WNM, whether and how matter is exchanged between these two phases, with the aim to refine existing models of the interstellar medium (Heiles 2000, Hennebelle & Pérault 1999). We still lack data on the spatial structure of both the CNM and the WNM. In particular, it is debated whether the cold and warm phases are mixed at small scale (inside a cloud) or whether they have different distributions. Another open question is the exact value of the kinetic temperature for both phases. Determinations of the kinetic temperature for the WNM conclude to quite “low” temperatures compared to model calculations ($\sim$ 6000K vs 8000 K), and to the presence of gas in the thermally unstable range (Carilli et al. 1998, Fitzpatrick & Spitzer 1997, Heiles 2000).

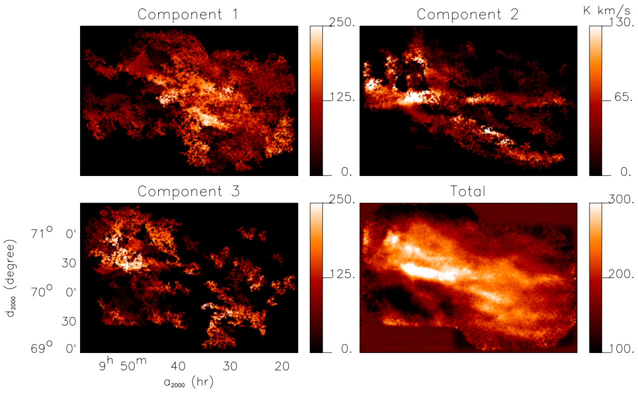

Figure 1. Maps for the three velocity components identified in a high latitude cirrus cloud, and total of the three components (Miville-Deschênes et al. 2001). These data have been obtained with the DRAO interferometer. The intensity is given in Kkms^{-1} for all maps.

High resolution maps of the 21cm HI line, such as those obtained by the DRAO interferometer (Joncas et al. 1992) provide data on the spatial and velocity structure of HI clouds. For atomic hydrogen, the thermal and turbulent contributions to the line width are similar in the CNM, and since the line is optically thin, HI maps give a direct view of the column density distribution. The best targets to study the thermal and spatial structure of the diffuse ISM are high latitude diffuse clouds, or cirrus, to minimise the confusion along the line of sight. Individual velocity structures, or components, are identified in the line profile from their spectral properties (central velocity, line width). Figure 1 shows observations obtained towards a high latitude cirrus (Miville-Deschênes et al. 2001). Three velocity components have been identified, the line intensity (which is proportional to the column density) is shown separately in the first three panels, and the total intensity is shown in the last panel. For this particular source, the neutral gas shows a complex spatial and velocity structure, with long filaments in component 2 and a more patchy distribution for component 1 and 3. The sizes of the observed structures vary from $\sim$ 1° for the largest to $\sim$ 2$'$ for the

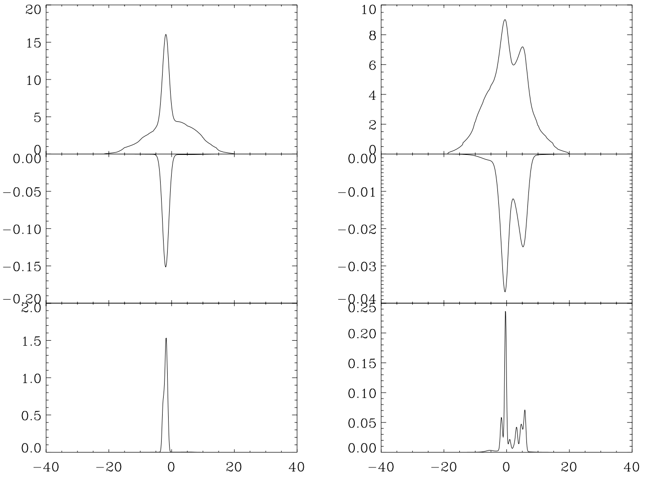

Figure 2. Prediction of HI emission spectrum (top), HI absorption spectrum (middle) and [CII] emission spectrum (bottom) obtained with a 1-D simulation of a thermally bistable gas. The left panels correspond to the pure hydrodynamic case, while the MHD case is considered in the right panels, (Hennebelle & Pérault 1999, 2000). The horizontal axis gives the radial velocity in kms^{-1}, the vertical axis gives the brightness temperature in Kelvins.

smallest (2 pc to 0.1 pc) for all velocity components in this nearby cloud (distance $\sim$ 100pc) .

To obtain a complete diagnostic of the physical conditions, it is necessary to combine HI data with sensitive observations of the fine structure lines of neutral and ionised carbon. These additional lines are excited mostly in the CNM, with a small contribution from the WIM for the 158 μm [CII] line. As shown in Figure 2, the contribution of thermal motions to the line width is smaller for carbon lines than for HI, while the non-thermal contribution stays the same. Fitzpatrick & Spitzer (1997) have used similar comparisons between HI emission and heavy ions absorption data to derive kinetic temperatures in diffuse clouds, but the comparison is difficult because of the large beam difference between emission and absorption. This difficulty will be easily overwhelmed with the large mapping capabilities of Herschel. By comparing HI, [CI] and [CII] line widths measured for the same area, the kinetic temperature can be deduced accurately from the line width.

The excitation of neutral and ionised carbon depends mostly on the gas pressure, which can be obtained once the kinetic temperature is known : the gas density can be derived from the ratio of the ^{3}P$_1$–^{3}P$_0$ and ^{3}P$_2$–^{3}P$_2$ [CI] lines at 609 and 370 μm. Because these lines are optically thin in diffuse regions, this diagnostic will not suffer from complex radiative transfer problems.

In diffuse interstellar clouds with moderate column density (N$_H \leq 2 \times 10^{21}$ cm^{-2}), the [CII] line is optically thin, hence the total cooling power radiated by ionised carbon depends linearly on its gas phase abundance. Using the [CI] and HI data to determine the kinetic temperature and gas density as described above, the abundance of gas phase carbon can be deduced from the brightness of the [CII] 158μm line. It is generally believed that the gas phase abundance of carbon and oxygen are fairly constant in diffuse clouds, based of the available absorption measurements (Sofia et al. 1998). There are however weak evidences that the gas phase carbon abundance decreases in translucent clouds where the gas becomes molecular (Snow et al. 1998, Jansen et al. 1996). Direct maps of the gas phase abundance of carbon would be a very valuable tool to understand the physics of depletion and the formation of grain mantles.

From maps of high latitude diffuse clouds, we expect that Herschel will determine accurately the physical properties of the CNM and WNM phases (density, kinetic temperature, thermal pressure, velocity field) and map their small scale variations. Fluctuations of the interstellar pressure have been identified by Jenkins et al. 1983 in their survey of neutral carbon UV absorption lines. Do these fluctuations appear at small scale (inside a cloud) as well, or are they due to some large scale physical processes ? There is no clear cut answer due to the lack of spatial information.

With a complete diagnostic of the physical conditions and a good description of the spatial structure, comparison with models will be more efficient. From a theoretical side, it is easier to model atomic clouds than molecular clouds since the chemistry is much simpler. The origin of the conspicuous small scale structure in diffuse clouds is almost certainly due to the turbulent velocity field, though other mechanisms have been proposed (Pfenniger & Combes 1994) The role of turbulence is not limited to the smallest scale but pertains to the whole hierarchy of interstellar clouds. Current models for the structure of interstellar clouds favour a turbulent origin (Vàzquez-Semadeni et al. 1995). Hennebelle & Pérault (1999) (see also Hennebelle & Pérault 2000) have shown how cold dense structures can form in a thermally unstable converging flow. For velocity perturbations slightly larger than the sound speed, the overpressure is large enough to trigger the phase transition from the WNM to the CNM. Examples of the line profiles obtained for cold structures just formed in the WNM are shown in Figure 2. Though condensation is more difficult in a magnetised fluid, Hennebelle & Pérault (2000) conclude that the formation of CNM structures is always possible. The spatial distribution of the cold condensations as well as the temperature distribution of neutral hydrogen are predicted to be different in the two cases : Fig. 2 illustrates the difference in HI and [CII] line profiles between the pure hydrodynamic case (left panels) and the MHD case (right panels). High resolution [CII] data may provide interesting information on the role of the interstellar magnetic field on the gas dynamics.

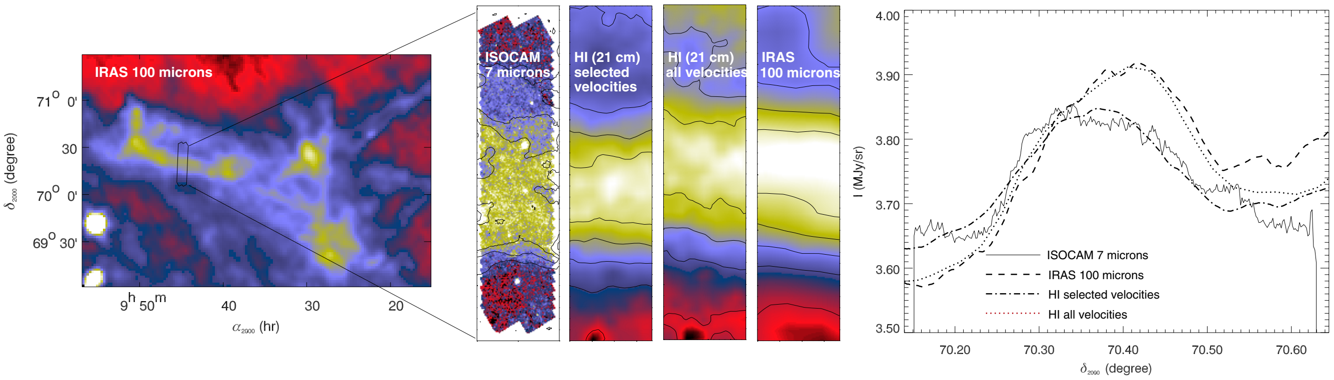

Figure 3. Comparison of the HI 21cm emission, IRAS 100µm emission and ISOCAM 7µm emission in the Ursa Major cirrus (middle). The large scale IRAS 100µm map is shown in the left panel. The right panel presents the same data along a N-S cut. Whereas the 100µm emission, is extremely well correlated with the total HI emission, the emission from small dust grains, mapped with ISOCAM, is more intense in a particular velocity component, identified as component 2 in Figure 1 (Miville-Deschênes et al., 2001).

2.3. ABUNDANCES

Together with the fine structure lines of atomic oxygen at 63 and 145 μm, the fine structure line of ionised carbon at 158 μm is the most important cooling line of diffuse atomic gas. At thermal equilibrium, heating balances cooling and variations of the [CII] brightness indicate small scale variations of the heating rate. In diffuse gas, the most efficient heating mechanism is the ejection of electrons from small dust particles due to the photo-electric effect (e.g. Wolfire et al. 1995). The smallest particles are the most efficient for this mechanism due to their larger surface/area ratio. Images towards a cirrus cloud near Ursa Major have been obtained in the mid-IR with the Infrared Space Observatory (ISO) and compared with HI and far infrared data (Fig.3). Whereas the total HI emission correlates extremely well with the far infrared thermal emission of large grains, the correlation breaks down for the small grains emitting in the mid-IR. A good correlation between the mid-IR and HI emission is recovered for a particular velocity component, identified as component 2 in Fig.1 (Miville-Deschênes et al. 2001). The abundance of small dust particles appears to be enhanced by a factor of five in this velocity component, compared to the average over all velocities. In a turbulent flow, the small dust particles do not remain coupled to the gas, and their abundance may fluctuate (Falgarone & Puget 1995). Do the fluctuations of the abundance of small dust particles reveal variations of the size distribution only, or are they accompanied by variations of the gas phase carbon abundance ? How frequent is this phenomenon ? Are these fluctuations related to variations of the physical parameters ? of the velocity field ? Observations with Herschel, coupled with high resolution dust maps obtained with ISO or SIRTF, will be uniquely matched to answer these questions.

2.4. PHOTO DISSOCIATION REGIONS - DYNAMICS

Most models of photo-dissociation regions (PDRs) are static, and use a pure gas phase chemistry, but other physical effects could play a role in these regions. Gerin et al. 1998 and Lemaire et al. 1999 have measured the line profile of the [CII] 158 μm and H_2 v=1-0 S(1) 2.12 μm lines respectively, in NGC 7023. There is a clear velocity gradient through the PDR which is not taken into account by models. Photodissociation and evaporation of molecular gas from the molecular cloud could explain this gradient. If this example is not unique, the static description of PDRs would not be valid anymore, and should be replaced by dynamical models including advection of cold molecular into the PDR and evaporation of gas. PDR are good regions to probe how kinetic energy can be fed into dense interstellar clouds : from observations of the carbon recombination lines, combined with [CII] and [CI] data, a low level of turbulence is found in the C^+ region, which contrasts with the larger velocity dispersion in the molecular gas (Wyrowski et al. 2000).

The impact of such dynamical phenomenon on the structure and chemistry of interstellar gas is not well understood as most models focus on either the chemistry or the dynamics separately. With the possibility of measuring detailed line profiles for all species dominating the gas cooling, a quantitative assessment of the role of gas dynamics will become possible. Conclusions based on bright photo-dissociation regions will be valid for the diffuse interstellar gas as a whole. For instance, the dissipation of turbulence is an additional heating source, highly localised in specific regions of a turbulent flow (Pety & Falgarone 2000). Measurements of the main cooling lines will help to quantify the impact of this additional heating source on the properties of diffuse interstellar gas.

3. CHEMISTRY

3.1. HYDRIDES

From SWAS and ISO observations, it is now known that absorption features are common at far infrared and submillimetre wavelengths (cf. G. Melnick's contribution). Many ground state transitions of hydrides lie in the HSO domain. In standard astrochemical networks, hydrides, as CH or OH, are present in diffuse gas as soon as molecular hydrogen is formed. These species are identified in the interstellar medium since the 40's, but observations in the visible are limited to lines of sight towards bright massive stars. Observations in the far infrared/sub-millimetre domain will give access to many more lines of sight for absorption measurements and to the possibility of detecting emission features in dense gas.

The species of interest include stable hydrides, CH, HF, OH, H_2O, as well as unstable species CH^+, H_2O^+, etc. CH^+ requires high temperatures to be formed efficiently, which can be found locally in shocks, or where the dissipation of turbulence is the largest (Joulain et al. 1998). Since CH^+ is destroyed very rapidly, its excitation and velocity distribution may keep a memory of its formation mechanism (Black 1998). The first two rotational lines of CH^+ lie too close to water lines to be observed from the ground, but appear at favourable frequencies for Herschel. CH^+ appears to be a very promising species for diffuse interstellar medium studies.

For all strong absorption features, monitoring of the line profile may give new information on the small scale structure of the intervening clouds. Such experiments have been performed on molecular lines observed in the radio (Faison et al. 1998, Liszt & Lucas 2000) as well as in the visible (Lauroesch et al. 2000) domain. In some cases, variations of the opacity of particular velocity components are seen which reveal the presence of velocity structures at tiny scale (≤ 100 AU). Similar studies performed on the dust extinction conclude to the absence of extinction fluctuations larger than $\delta A_V / A_V = 5\%$ at small scale (Boissé et al. 1999). These conflicting results point to the necessity to address the question better. With the long lifetime of HSO similar studies could be carried towards more distant continuum sources, to monitor the line profile of abundant chemical species.

3.2. LARGE MOLECULES

The inventory of the molecules present in the interstellar medium is fairly incomplete. For example, the identification of the carriers of most Diffuse Interstellar Bands (DIBs) is still pending. The full opening of the far infrared and sub-millimetre domain with HSO will offer the opportunity to search for many new species in the diffuse interstellar gas. Other contributions in this volume (C. Joblin, J. Goicochea) present detailed calculations of the expected spectra for some molecules.

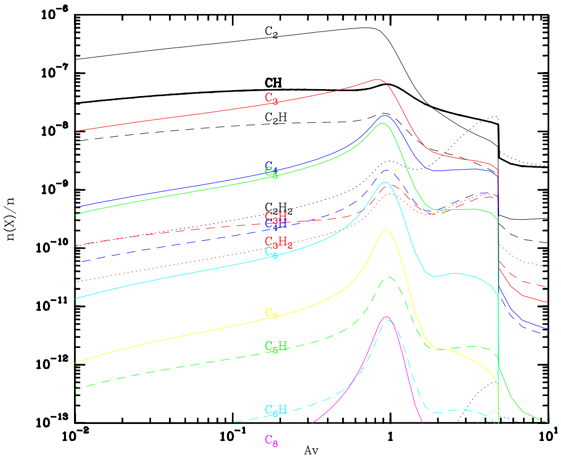

Figure 4. Prediction of the abundance of linear carbon chains from C_2 (black) to C_8 (purple) using the New Neutral Neutral chemical model from E. Herbst, for a diffuse gas with moderate density ($n_H = 10^3$ cm^{-3}), illuminated by the standard ISRF. Carbon chains are shown with full lines, C_nH species with dashed lines and C_nH_2 species with dotted lines. There is a clear tendency to have C_n species more abundant than the corresponding C_nH species, more abundant than the corresponding C_nH_2 species. Species up to C_6 reach abundances larger than 10^{-10} for $A_V \sim 1$.

It is expected that some large molecules, bridging the gap between the known gas phase species and the Polycyclic Aromatic Hydrocarbons (PAHs), survive in the diffuse IS. Large molecules are good candidates for some Diffuse Interstellar Bands, though no definitive identification has been made yet. The strength of these absorption features require quite high abundances for their carriers (Herbig 1995, 2000). Carbon is generally thought to be a major constituent of the DIBs carriers, therefore, carbon chains and other hydrocarbons have been suggested as possible carriers (e.g. Thaddeus 1995, Ball et al. 2000). Carbon chains (linear or cyclic) are also very good candidates for Herschel since they have low lying vibrational modes in the far infrared. Hence absorption measurements in the far infrared will allow to detect symmetric species which escape detections in the radio domain. For example, the C_3 radical has been recently detected towards the Galactic Centre by ISO (Cernicharo et al. 2000).

It is possible to use gas phase chemical models to obtain predictions for the abundances of some large molecules. Though the chemical network have not been as extensively tested for these large species as they are for smaller species, these models provide some inputs to drive the observational effort. For example, we show in Figure 4 predictions for a diffuse cloud obtained with the "New Neutral Neutral" chemical network from E. Herbst (Terzevia & Herbst 1998, Turner et al. 2000) and a PDR model (Le Bourlot et al. 1993). The same code using the UMIST95

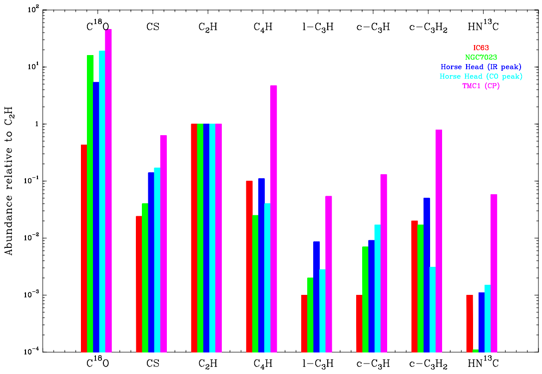

Figure 5. Abundances of hydrocarbons, C_3H, C_4H, C_3H_2, and other species, relative to CCH in TMC-1(purple) and in three photo-dissociation regions, IC 63(red), NGC 7023(green), Horsehead nebula(blue) (Fossé 2001). For all PDRs, [c-C_3H_2]/[CCH] ~ 0.03 *and [C_4H]/[CCH]* ~ 0.07

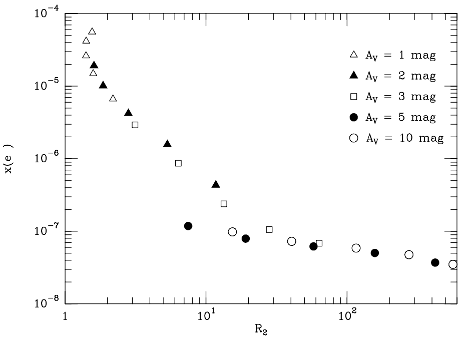

Figure 6. Prediction of the abundance ratio of cyclic versus linear C_3H_2, R_2 as a function of the electronic density, using the UMIST95 file of chemical reaction rates. Series of models have been calculated with different extinction Av, and gas densities. Different symbols refer to different Av (Fossé et al. 2001).

network predicts the same trends though the exact abundances differ by up to an order of magnitude. From E. Herbst's model, carbon chains up to C_6 reach a significant abundance ($\geq 10^{-10}$) in diffuse gas (Av $\sim$ 1 mag.). There is a clear pattern with C_n species being more abundant than C_nH species, which are themselves more abundant than C_nH_2 species. C_n species can not be detected in the radio domain as they have no permanent dipole moment, but could be seen in the diffuse ISM with Herschel through their ro-vibrational far infrared spectrum. Recent observations of hydrocarbons towards photo-dissociation regions have given encouraging results in this direction as $c\!-\!C_3H_2$ and C_4H have been clearly detected, at an abundance level larger than model predictions (Fossé 2001, Figure 5).

In addition to completing the chemical inventory, the detection of new interstellar species in diffuse gas may provide interesting diagnostics of the physical conditions. For example, Fossé et al. 2001 have shown that the abundance ratio of the cyclic and linear isomers of C_3H_2 is predicted to be a sensitive function of the electronic abundance (Figure 6).

4. DUST LIFE CYCLE IN THE INTERSTELLAR MEDIUM

The knowledge of the dust properties in the diffuse gas has progressed with the analysis of the COBE survey since the emission above the Galactic Plane is dominated by diffuse interstellar gas. Still, the properties of dust in the sub-millimetre and far infrared domain remain poorly known compared to other wavelengths. Other contributions in this volume develop this subject (J.Ph. Bernard, I. Ristorcelli, F. Boulanger, M.A. Miville-Deschênes, and B. Stepnik).

The far infrared spectrum of diffuse gas associated with HI emission obtained from COBE/FIRAS data is extremely well fitted by a modified Planck function with a mean temperature of 17.5 K and an emissivity proportional to the square of the frequency (Boulanger et al. 1996, Lagache et al. 1999). The COBE data have also been used to study the properties of dust in both ionised and molecular regions. Observations of dust in the various phases of the interstellar medium is important to identify and understand how the dust grains evolve after they are released in the ISM. The pattern of elemental depletions shows a clear trend of lower depletions in more diffuse gas. This is interpreted as the sign of the erosion and destruction of dust grains in low density, hot gas, due to shocks and other processes (Jones et al. 1996).

4.1. COLD DUST IN MOLECULAR CLOUDS

Whereas the dust evolution in hot gas is controlled by destruction processes, such as fragmentation, sputtering and erosion, coagulation of dust grains and accretion of gas phase species as mantles are the main evolutionary processes in cold gas. Studies of dust thermal emission in the far infrared/sub-millimetre wavelength range have permitted to determine accurately the dust temperature and emissivity law at large angular scales. In atomic neutral gas, the dust temperature is fairly constant at $T_d \sim 17.5$ K , while cold dust appears in molecular gas with $T_d \leq 15$ K. The transition from "normal" to "cold" dust is sharp at large angular resolution, and coincides with the transition from atomic to molecular gas (Abergel et al. 1994, Lagache et al. 1998). Cold dust emission has also been detected in the high latitude cirrus Polaris by the PRONAOS balloon experiment (Bernard et al. 1999). In this low column density gas almost transparent to the interstellar radiation, the existence of cold dust is surprising given the known optical properties. A larger emissivity in the far infrared (up to a factor of 3) is required to cool down the dust to the observed temperature $T_d \sim 12$K. The most likely explanation for this behaviour is the coagulation of small dust grains into fluffy aggregates with a much larger emitting surface, hence a larger emissivity in the far infrared.

4.2. THE ROLE OF THE HERSCHEL SPACE OBSERVATORY

It is clear that the previous studies lack angular resolution to track down the origin of the observed evolution of dust properties. With the broad wavelength coverage from PACS and SPIRE, combined eventually by data at shorter wavelength obtained from ISO, SIRTF or SOFIA, it will be possible to study the small scale variations of the dust properties as a function of the environment : from the warm ionised medium to the neutral gas to diffuse molecular gas to dense cores. This requires finely sampled large scale maps of the diffuse continuum emission, in the 6 photometric bands available, to obtain a good description of the spectral energy distribution of the dust emission.

5. IMPLICATIONS FOR EXTERNAL GALAXIES

The energy exchanges between stars and gas occur on a wide variety of scales in galaxies. With its significant filling factor, the diffuse interstellar medium is an ubiquitous component, which affects the global properties of galaxies, both for the line and continuum emission. From ground based and KAO/ISO data, diagnostics of the physical conditions in nearby galaxies have been obtained from CO, [CI] and [CII] data (e.g. Gerin & Phillips 2000). Using ISO-LWS, emission from diffuse atomic gas has been clearly identified in the disk of the spiral galaxies NGC 1313 and NGC 6946 (Contursi et al. 1999, Figure 7). In NGC 6946, the low level emission corresponds to diffuse emission while the high level emission is found in photo-dissociation regions. Large scale [CII] have been obtained for the inner Milky Way (Nakagawa et al. 1998). As for NGC 6946, there is both a diffuse [CII] component and bright peaks associated with known star forming regions. As a whole the diffuse [CII] emission originates both in surfaces of molecular clouds (PDRs) and in atomic clouds (Mochizuki & Nakagawa 2000), with a small contribution from diffuse HII regions. Using a detailed model of the interstellar medium Sauty et al. 1998 reached a similar conclusion for NGC 6946.

For external galaxies, contributions of ionised gas, the Cold Neutral Medium, and molecular photo dissociation regions (PDRs) to the large scale emission in the fine structure lines ([OI], [NII], [CII], [CI], etc.) and the far infrared continuum are always mixed in the beam. The strong correlation between the [CII] and mid-IR emission in galaxies (Hélou et al. 2001) demonstrates the importance of photo processes for the energy budget in galaxies. The vertical structure and filling factor of the ISM determine the optical depth of the galactic disks to UV photons, hence the conversion of UV to far infrared radiation. With their larger filling factor, the diffuse ISM components and mostly the warm components are important phases for the thermal balance of galaxies at large scale. Evidences for the two neutral phases have been found in external galaxies with properties very different from the Milky Way. In the Small Magellanic Cloud (SMC), the relative proportions of WNM and CNM are biased towards the WNM, but the CNM is cooler (Dickey et al. 2000). These properties are consistent with available models which predict that the phase transitions should occur at a higher pressure in lower metallicity gas. As a consequence the CNM is expected to be less extensive. The two phases are also present in Damped Lyman Alpha systems (e.g. Lane et al. 2000).

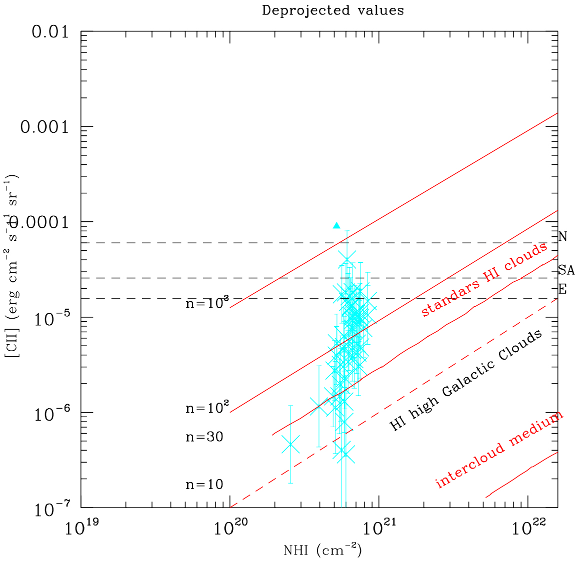

Figure 7. ISO-LWS [CII] 158μm surface brightness as a function of the de-projected HI column density in the disk of NGC 6946. The filled triangle corresponds to the galaxy nucleus and the three dashed lines to the surface brightness detected with the KAO for the nucleus (N), spiral arms (SA) and extended emission (E). Red lines show the expected [CII] brightness for gas at different densities. The low level emission corresponds to diffuse emission while the high level emission is found in photo-dissociation regions (Contursi et al. 2000).

Our Galaxy, the Milky Way, remains the basic template for the properties of the ISM used in extragalactic studies. Detailed models of the ISM properties are available and observations at high spatial and spectral resolution are possible, to identify properly the ISM phases. Global properties, valid for external galaxies, can be obtained in the Milky Way without the need of a complete survey of the Galactic plane. The variations of the ISM properties as a function of Galactic Latitude and Longitude give access to the basic mechanisms at work in the ISM and their relative importance. These numbers can then be fed into detailed models to be applied to the global energy budgets in external galaxies, for a better understanding of galaxy evolution.

ACKNOWLEDGEMENTS

This paper has benefited from many discussions with, and contributions from F. Boulanger, A. Contursi, E. Falgarone, D. Fossé., E. Herbst, J. Le Bourlot, M. Pérault, G. Pineau des Forêts and E. Roueff.

REFERENCES

Abergel A., Boulanger F., Mizuno A., Fukui Y., 1994, ApJ 423, L59.

Ball C.D., Mc Carthy M.C., Thaddeus P., 2000, ApJ 529, L61.

Bernard J. P., Abergel A., Ristorcelli I., Pajot F., Torre J. P., Boulanger F., Giard M., Lagache G., Serra G., Lamarre J. M., Puget J. L., Lepeintre F., Cambrésy L., 1999, A&A 347, 640.

Black J.H., 1998, *The molecular astrophysics of stars and galaxies*, T.W. Hartquist and D.A. Williams eds, Clarendon Press.

Boissé P., Thoraval S., Duvert G., Cuillandre J.C., Pagnai L., 1999, in *H_2 in space*, F. Combes, G. Pineau des Forêts eds, Cambrige University Press.

Boulanger F., Abergel A., Bernard J.-P., Burton W. B., Désert F.-X., Hartmann D., Lagache G., Puget J.-L., 1996, A&A 312, 256.

Carilli C.L., Dwarakanath K.S., Goss W.M., 1998, ApJ 502, L79.

Contursi A., Brauher J., Helou G., 2000, 1st Euroconference on the Evolution of Galaxies: I. Observational Clues, eds. J.M. Vichez, G. Stasinska and E. Perez .

Cernicharo J., Goicoechea J. R, Caux E., 2000, ApJ 534, L199.

Colbert J. W., Malkan M. A., Clegg P. E., Cox P., Fischer J., Lord S. D., Luhman M., Satyapal S., Smith H. A., Spinoglio L., Stacey G., Unger S. J., 1999, ApJ 511, 721.

Dickey J.M., Mebold U., Stanimirovic S., Staveley-Smith L., 2000, ApJ 536, 756.

Faison M. D., Goss W. M., Diamond P. J., Taylor G. B., 1998, AJ116, 2916.

Falgarone E., Puget J.L., 1995, A&A 293, 840.

Ferrière K., 1998, ApJ 497, 759.

Fitzpatrick E.L., Spitzer L., 1997, ApJ 475, 623.

Fixsen D.J., Bennett C.L., Mather J.C., 1999, ApJ 526, 207.

Fossé D., 2001, PhD thesis, Université Paris 6.

Fossé D., Cernicharo J., Gerin M., Cox P., ApJ in press.

Gerin M., Phillips T.G., Keene J., Betz A.L., Boreiko R.T., 1998, ApJ 500, 329.

Gerin M., Phillips T.G., 2000, ApJ 537, 644.

Haffner L. M., Reynolds R. J., Tufte S. L., 1999, ApJ 523, 223.

Heiles C., 2000, *Fourth Tetons Conference : Galactic structure, Stars and the Interstellar Medium*, M.D. Bicay & C.E. Woodward eds.

Hélou G., Malhotra S., Hollenbach D.J., Dale D.A., Contursi A., 2001, ApJ in press.

Hennebelle P., Pérault M. 1999, A&A 351, 309.

Hennebelle P., Pérault M. 2000, A&A 359, 1124.

Herbig G.H., 1995, ARAA 33, 19.

Herbig G.H., 2000, ApJ 542, 334.

Jansen D.J., van Dishoeck E.F., Keene J., Boreiko R.T., Betz A.L., 1996, A&A 309, 899.

Jenkins E. B., Jura M., Loewenstein M., 1983, ApJ 270, 88.

Joncas G., Boulanger F., Dewdney P.E., 1992, ApJ 397, 165.

Jones A.P., Tielens A.G.G.M., Hollenbach D.J., 1996, ApJ 469, 740.

Joulain K., Falgarone E., Pineau des Forêts G., Flower D., 1998, A&A 340, 241.

Kulkarni S.R., Heiles C., 1987, in *Interstellar processes*, D.J. Hollenbach & H.A. Thronson eds, D. Reidel, p 87.

Lauroesch J. T., Meyer David M., Blades J. C., 2000, ApJ 543, L43.

Lagache G., Abergel A., Boulanger F., Puget J.L., 1998, A&A 333, 709.

Lagache G., Abergel A., Boulanger F., Désert F. X., Puget J. L., 1999, A&A 344, 322.

Lane W.M., Briggs F.H., Smette A., 2000, ApJ 532, 146.

Lagache G., Haffner L. M., Reynolds R. J., Tufte S. L., 2000, A&A 354, 247.

Le Bourlot J., Pineau Des Forêts G., Roueff E., Flower D. R., 1993, A&A 267, 233.

Lemaire J. L., Field D., Maillard J. P, Pineau Des Forêts G., Falgarone E., Pijpers F. P., Gerin M., Rostas F., 1999, A&A 349, 253.

Liszt H.H., Lucas R., 2000, A&A 355, 333.

Maloney P.R., Hollenbach D.J., Tielens A.G.G.M., 1996, ApJ 466, 561.

Mathis J.S., 2000, ApJ 544, 347.

Miville-Deschênes M.A., 1999, PhD Thesis, Université Paris-Sud.

Miville-Deschênes M.A., Boulanger F., Joncas G., Falgarone E., 2001, A&A submitted.

Mochiguzi K., Nakagawa T., 2000, ApJ 535, 118.

Nakagawa T., Yamashita Y., Doi Y., Okuda H., Shibai H., Mochizuki K., Nishimira T., Low F.J.,1998, ApJ supl. 115, 259.

Pety J., Falgarone E., 2000, A&A 356, 279.

Pfenniger D., Combes F., 1994, A&A 285, 94.

Rand R.J., 1998, ApJ 501, 137.

Sauty S., Gerin M., Casoli F., 1998, A&A 339, 19.

Slavin J. D., McKee C. F., Hollenbach D. J., 2000, ApJ 541, 218.

Snow T.P., Hanson M.M., Black J.H., van Dishoeck E. F., Crutcher R.M., Lutz B.L., 1998, ApJ 496, L113 and ApJ 504, L 55

Sofia U.J., Fitzpatrick E., Meyer D.M., 1998, ApJ 504, L47.

Terzevia R., Herbst E., 1998, ApJ 501, 207.

Thaddeus P., 1995, in it The Diffuse Interstellar Bands, A.G.G.M. Tielens and T.P. SNow eds.

Turner B.E., Herbst E., Terzevia R., 2000, ApJS 126, 427.

Vazquez-Semadeni E., Passot T., Pouquet A., 1995, ApJ 441, 702.

Wolfire M. G., Hollenbach D., McKee C. F., Tielens A. G. G. M., Bakes E. L. O., 1995, ApJ 443, 152.

Wood K., Reynolds R.J., 1999, ApJ 525, 799.

Wyrowski F., Walmsley C. M., Goss W. M., Tielens A. G. G. M., 2000, ApJ 543, 245.